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# DIFFUSIVE, ELECTROSTATIC CONCENTRATION OF DISINTEGRATION PRODUCTS OF INERT GASES IN VORTEX FLOW

THOMAS A. KORJACK

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The problem of steady-state mass transfer of decaying products resulting from the disintegration of an inert gas is considered for a vortex pipe flow configuration under variable electrostatic fields. The flow configuration consists of two smoothly joined sections, one stationary and the other rotating with constant angular velocity. The products of disintegration are filtered out at far upstream ($z = -\infty$), but are again generated by radioactive decay of a flowing inert gas along the tube. Bulk concentrations result due to electrostatic force and diffusion. It was found that increasing the electrostatic charge caused a decrease in penetration; also, a decrease in charge profile was accompanied by an increase in potential since the particles become annihilated at the boundaries.

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## 1. INTRODUCTION

When small particles suspended in a gaseous medium flow through a long cylindrical tube or conduit, the random Brownian movement, or diffusion of the particles which may be submicron aerosols, atoms, or ions, may bring them into contact with the walls, where they adhere or lose their charge. From the fraction of particles penetrating the conduit, the diffusion coefficient and particle size may be calculated with the use of the appropriate relations. The case in hand is when no particles enter the conduit, and formation in flight occurs within the containment; this arises when air containing a radioactive, rare gas enters the conduit through a high-efficiency filter located far upstream from the tube configuration. As the radioactive gas flows through the geometry, it decays, giving rise to the steady production of a certain number of daughter atoms per unit volume. Unlike the radioactive gas, the daughter atoms adhere to the wall and are lost by diffusion. This dispersion of atoms may be considered to be an atomic aerosol (Tan and Hsu 1971) since it has the same property as submicron aerosols in that they can be collected at a surface. The radioelements diffuse to the tube walls where they decay into other radioelements.

Formation in flight diffusion equations have been derived for cylindrical tubes (Tan and Hsu 1971; Berezhnoi and Kirichenko 1964) and for flat channels (Berezhnoi and Kirichenko 1964), including the mass transfer of aerosols with axial diffusion in narrow rectangular channels (Tan and Hsu 1972).

Swirling flows related to ducts have been studied extensively (Fromm 1963; Pao 1967; Textor 1968). A well-defined configuration of a confined axially decaying vortex flow was introduced in a study by Lavan, Nielsen, and Fejer (1969). Also, Tung and Soo (1973) presented a study applying the fluid phase relations of Lavan, Nielsen, and Fejer (1969) to the case of a gas-solid suspension.

The present study utilizes the geometry of Lavan, Nielsen, and Fejer (1969) (see Figure 1) to study the case of a laminar swirling flow of atomic particles formed in flight under electrostatic field effects. The fluid phase is assumed incompressible and fully developed at both far upstream and downstream positions from the juncture of the two pipes. A forced vortex is generated by the rotating pipe, and it decays as the flow passes through the stationary duct because of wall surface friction. At far downstream, the swirl vanishes, and it is assumed that the axial velocity converts back to the fully

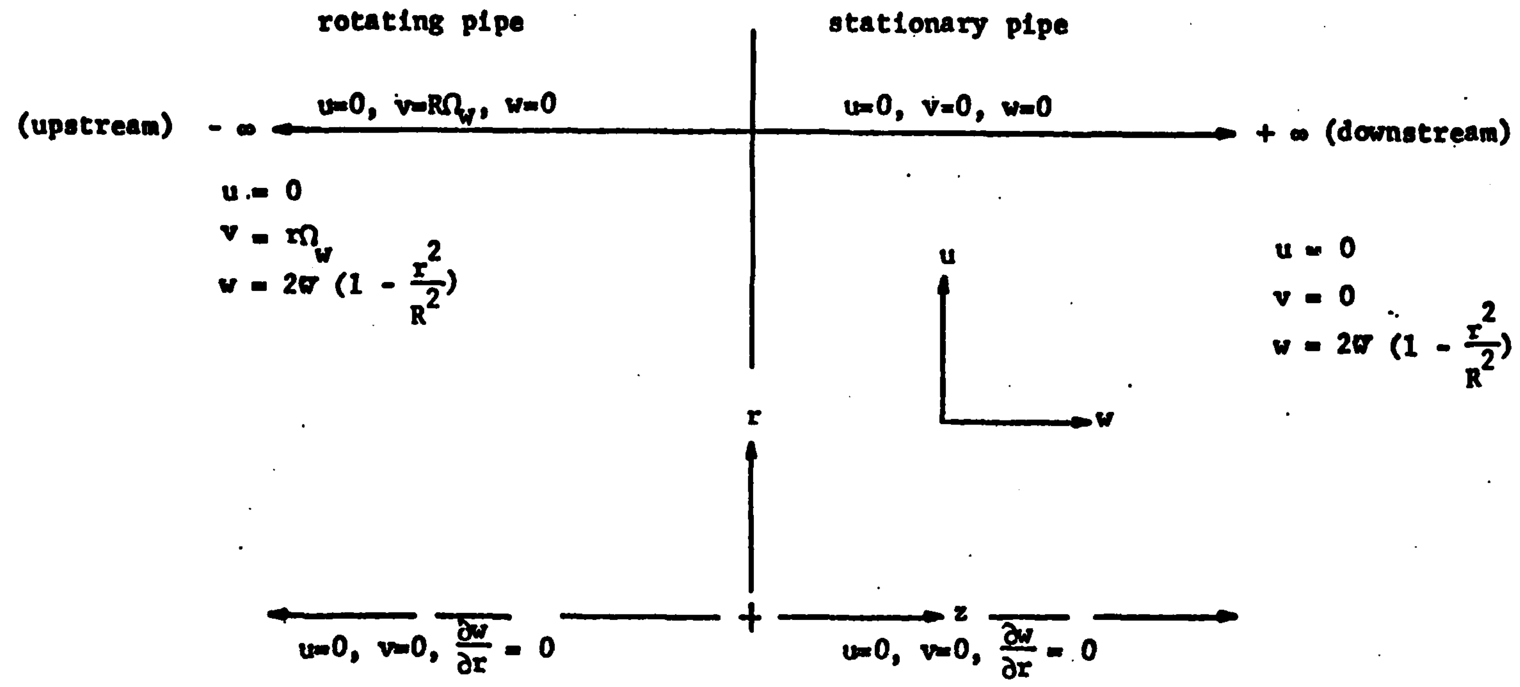


Figure 1. Coordinate System and Boundary Values.

developed laminar parabolic profile. The particle concentration is assumed low enough so that the effect on the fluid phase due to the presence of the particles is negligible (Soo 1967). The solutions of the fluid phase velocities can then be effectively utilized to solve for the particulate relations. The fluid phase velocities are obtained by solving the Navier-Stokes equations numerically.

## 2. FORMULATION

The motion of the fluid phase is given by solving the continuity and the Navier-Stokes equations for a steady, laminar, incompressible, and axisymmetric swirling flow. The solution is given in terms of the radial, tangential, and axial components of the fluid velocity ($u$, v, $w$ in $r$, $\theta$, and $z$ coordinates, respectively), pressure $p$, the density $\rho$, and $\nu$, the kinematic viscosity of the fluid phase material. Hence, the fluid phase relations are (Schlichting 1968):

$$u \frac{\partial u}{\partial r} - \frac{v^2}{r} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \nu \left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(ru)\right) + \frac{\partial^2 u}{\partial z^2}\right]; \qquad (1)$$

$$u \frac{\partial v}{\partial r} + \frac{uv}{r} + w \frac{\partial v}{\partial z} = \nu \left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(rv)\right) + \frac{\partial^2 v}{\partial z^2}\right]; \qquad (2)$$

$$u \frac{\partial w}{\partial r} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \nu \left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w}{\partial z}\right) + \frac{\partial^2 w}{\partial z^2}\right]; \qquad (3)$$

and the continuity relation is

$$\frac{\partial}{\partial r}(ru) + \frac{\partial}{\partial z}(rw) = 0. \qquad (4)$$

The expression describing the steady-state mass diffusion of a constituent in a generating but nonreacting binary gas mixture under electrostatic influences flowing through the system described in Figure 1, assuming azimuthal symmetry and constant coefficient of diffusion is

$$u\frac{\partial c}{\partial r} + w\frac{\partial c}{\partial z} = D_p\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial c}{\partial r}\right)\right] + \frac{1}{F}\left[\frac{\partial}{\partial r}\left(\frac{cq}{m_p}\frac{\partial \phi}{\partial r}\right)\right] + \frac{c}{Fr}\left(\frac{q}{m_p}\right)\frac{\partial \phi}{\partial r} + \dot{Q}, \qquad (5)$$

coupled with the Poisson equation,

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \phi}{\partial r}\right) = -\frac{c}{\varepsilon_o}\left(\frac{q}{mp}\right), \qquad (6)$$

where $F$ is the inverse of relaxation time constant defined as

$$F = 9\bar{\mu} / 2a^2\,\bar{c}\,, \qquad (7)$$

where $\bar{\mu}$ and $\bar{c}$ are the viscosity of the fluid and material density of the particulate phase, respectively, and $a$ is the radius of a particle.

The boundary conditions of the solution take the following forms:

$$\text{at } r = 0: u = v = \frac{\partial w}{\partial r} = \frac{\partial c}{\partial r} = \frac{\partial \phi}{\partial r} = 0; \qquad (8)$$

(centerline)

$$\text{at } r = R_o: u = w = c = \phi = 0;\ v = \begin{Bmatrix} R_o\Omega, & -\infty \le z \le 0 \\ 0, & 0 < z \le +\infty \end{Bmatrix}; \qquad (9)$$

(wall)

$$\text{at } z = -\infty: u = c = \phi = 0;\ v = r\Omega,\ w = 2\bar{w}\left(1 - \frac{r^2}{R_o^{\ 2}}\right); \qquad (10)$$
(far upstream)

$$\text{at } z = +\infty: u = v = 0;\ w = 2\bar{w}\left(1 - \frac{r^2}{R_o^{\ 2}}\right); \qquad (11)$$
(far downstream)

where $\Omega$ is the constant angular velocity of the rotating pipe, $\bar{w}$ is the mean axial flow velocity, and $R_o$ is the radius of the pipe.

The flow configuration, together with the boundary conditions, is shown in Figure 1. The pipe section at the left of the r-axis rotates with constant angular velocity $\Omega$ and creates the swirl, while the pipe section at the right is held stationary. At $z = 0$, the two pipes join smoothly with no effect on the flow. At far upstream ($z = -\infty$) and downstream ($z = +\infty$), the flow is assumed fully developed.

Since the radioelements are completely annihilated at the walls, $c = 0$ at $r = R_o$; also, because of the grounded walls, $\phi = 0$ at $r = R_o$ Furthermore, it is assumed that $c = 0$ at $z = -\infty$.

The following nondimensional forms may be introduced as:

$$R = r/R_o,\ Z = z/R_o,\ \Psi^* = \Psi/\Psi_w;$$

$$W = \frac{w}{\bar{w}/2},\ U = \frac{u}{\bar{w}/2},\ V = v/(R_o\Omega);$$

$$\zeta^* = \zeta R_o^3/\Psi_w,\ P = p/\left(\rho R_o^{\ 2}\Omega^2\right);$$

$$C^* = D_p c/\left(\dot{Q}R_o^2\right),\ \phi^* = q\,\phi/(m_p F D_p);$$

where $\Psi_w$ is the stream function at the wall. The Reynolds number is given by

$$Rey = \frac{4\Psi_w}{\nu R_o} = \frac{2\overline{w}R_o}{\overline{\nu}}, \tag{12}$$

and the swirl ratio is given by the ratio of the tangential velocity of the rotating pipe to the mean axial velocity,

$$S = \frac{R_o\Omega}{\overline{w}}. \tag{13}$$

The diffusive Peclet number is the ratio of the inertial to diffusive forces,

$$P_e = \frac{R_o\overline{w}}{D_p}, \tag{14}$$

and the electrostatic charge parameter is given by

$$\alpha = \frac{1}{4}\left(\frac{\dot{Q}R_o^2}{D_p}\right)\left(\frac{q}{m_p}\right)^2\frac{R_o^2}{\varepsilon_o F D_p}. \tag{15}$$

The classical numerical approach which converts the velocity components into stream function $\Psi$, vorticity $\zeta$, and circulation $\Gamma$ was chosen because of its well-established stability.

The relations for the fluid phase after they have been expressed in nondimensional form were cast into explicit finite difference molecules (Southwell 1940; Ames 1972) and solved by numerical relaxation yielding results consistent with Lavan, Nielsen, and Fejer (1969) and Tung and Soo (1973). As a result of the axial symmetry of the flow field, only the flow in the rectangular region defined by

$$D = \left[(R,X) \;\middle|\; 0 \le R \le 1 \text{ and } 0 \le X \le 1\right] \tag{16}$$

need be considered where $X$ is a mapping function given by Tung and Soo (1973) and used to transform the z-axis into the x-axis. On $D$ itself, parallel mesh points (41 x 41) were uniformly spaced by an amount $\Delta$ in both radial and axial directions. Initial assumed values for $\Gamma$, $\zeta$, and $\Psi$ were specified, then an iterative procedure consisting of sweeps of the interior mesh points was implemented until a convergence criteria (Forsythe and Wasow 1967) was satisfied.

The diffusion and Poisson equation can be written in nondimensional form as

$$\left(\frac{P_e}{2}\right)\left(U\frac{\partial C^*}{\partial R} + X' \, W\,\frac{\partial C^*}{\partial X}\right) = \frac{1}{R}\frac{\partial C^*}{\partial R} + \frac{\partial^2 C^*}{\partial R^2} + \frac{\partial \phi^*}{\partial R}\frac{\partial C^*}{\partial R} - 4\alpha C^{*2} + 1, \tag{17}$$

$$\frac{1}{R}\frac{\partial \phi^*}{\partial R} + \frac{\partial^2 \phi^*}{\partial R^2} = -4\alpha C^* \tag{18}$$

subject to

$$C^*\,(R,\,X{=}0) = \phi^*\,(R,\,X{=}0) = 0\,; \tag{19}$$

$$C^*\,(1,X) = \phi^*(1,X) = 0\,; \tag{20}$$

$$\frac{\partial C^*}{\partial R}\,(0,X) = \frac{\partial \phi^*}{\partial R}\,(0,X) = 0\,. \tag{21}$$

Defining $F(X)$ as the ratio of the total particle flux over a cross-section at distance $X$ from the far upstream position (at $z = -\infty$) to the rate of formation of the radioelements in the same element of the tube, we have

$$F(X) = \frac{1}{X}\int_0^1 W C^* R\,dR\,. \tag{22}$$

After the fluid phase is solved, the respective velocities can be implemented into the solution of the differential system encompassing Equations 17 to 21. Due to the universal stability of the implicit method, this parabolic system was expressed in terms of the implicit finite difference discretization technique such that the diffusion and Poisson equations take the forms, respectively,

$$\beta 1_{i,j} C^*_{i+1,j-1} + \beta 2_{i,j} C^*_{i+1,j} + \beta 3_{i,j} C^*_{i+1,j+1} + \beta 4_{i,j} \phi_{j-1} + \beta 5_{i,j} \phi^*_{j+1} = \Omega 1_{ij}; \tag{23}$$

$$\gamma 1_{i,j} \phi^*_{j-1} + \gamma 2_{i,j} \phi^*_{j} + \gamma 3_{i,j} \phi^*_{j+1} + 4\alpha C^*_{i+1,j} = 0, \tag{24}$$

where

$$\beta 1_{i,j} = -\left(\frac{P_e}{2}\right)\frac{U_{i+1,j}}{2\Delta R} + \frac{1}{2R_j \Delta R} - \frac{1}{(\Delta R)^2}; \tag{25}$$

$$\beta 2_{i,j} = \left(\frac{P_e}{2}\right)\frac{X'_{i+1,j} W_{i+1,j}}{\Delta X} + \frac{2}{(\Delta R)^2} + 4\alpha C^*_{i,j}; \tag{26}$$

$$\beta 3_{i,j} = \left(\frac{P_e}{2}\right)\frac{U_{i+1,j}}{2\Delta R} - \frac{1.0}{2R_j(\Delta R)} - \frac{1}{(\Delta R)^2}; \tag{27}$$

$$\beta 4_{i,j} = \frac{1}{2\Delta R}\left(\frac{C^*_{i,j+1} - C^*_{i,j-1}}{2\Delta R}\right); \tag{28}$$

$$\beta 5_{i,j} = -\frac{1}{2\Delta R}\left(\frac{C^*_{i,j+1} - C^*_{i,j-1}}{2\Delta R}\right); \tag{29}$$

$$\Omega 1_{i,j} = \left(\frac{P_e}{2}\right) \frac{X'_{i+1} W_{i+1,j} C^*_{i,j}}{\Delta X} + 1.0 \; ; \tag{30}$$

$$\gamma 1_{i,j} = \frac{1}{(\Delta R)^2} - \frac{1}{2(\Delta R) R_j} \; ; \tag{31}$$

$$\gamma 2_{i,j} = - \frac{2}{(\Delta R)^2} \; ; \tag{32}$$

$$\gamma 3_{i,j} = \frac{1}{(\Delta R)^2} + \frac{1}{2 R_j (\Delta R)} \; . \tag{33}$$

Convergence (Forsythe and Wasow 1967; Hornbeck 1975) was satisfied for all Peclet and electrostatic charge parameters, with respect to the mesh sizes considered ($\Delta X$, $\Delta R$ = 0.01, 0.025, 0.05). The sparse and unsymmetric system resulting from the finite difference expressions for the diffusion and Poisson system was solved by Gaussian elimination with full and partial pivoting with the aid of the Crout reduction technique.

## 3. RESULTS AND DISCUSSIONS

Since the fluid phase relations have already been solved (Lavan, Nielsen, and Fejer 1969; Tung and Soo 1973), they will not be discussed, except for the precision with which they matched the available comparable calculations, which was within 0.01% for most cases.

The effect of the electrostatic field parameter, $\alpha$, on the fraction of penetration over the complete axial distance from far upstream to far downstream positions can be seen in Figure 2. Clearly, the increase in charge causes a decrease in penetration, $F(X)$, since more atomic particles are attracted to the walls where they become completely annihilated.

Figure 3 represents the effect of the charge on the centerline concentration over the complete axial distance. A decrease in profile is accompanied by an increase in charge since the particles are lost at the boundary. Figure 4 identifies the greater electrostatic potential due to the increase in electric field.

Hence, the electrostatic charge parameter, $\propto$, has a significant impact upon nuclear particle deposition in vortex flow when $1 \leq Rey \leq 10$, $1 \leq S \leq 12$, $1 \leq P_e \leq 10$, and $1 \leq \propto \leq 10$, which represent an appreciable realistic range. Increasing $\propto$ increased deposition and potential, regardless of $Rey$, $P_e$ and $S$ variations within these ranges.

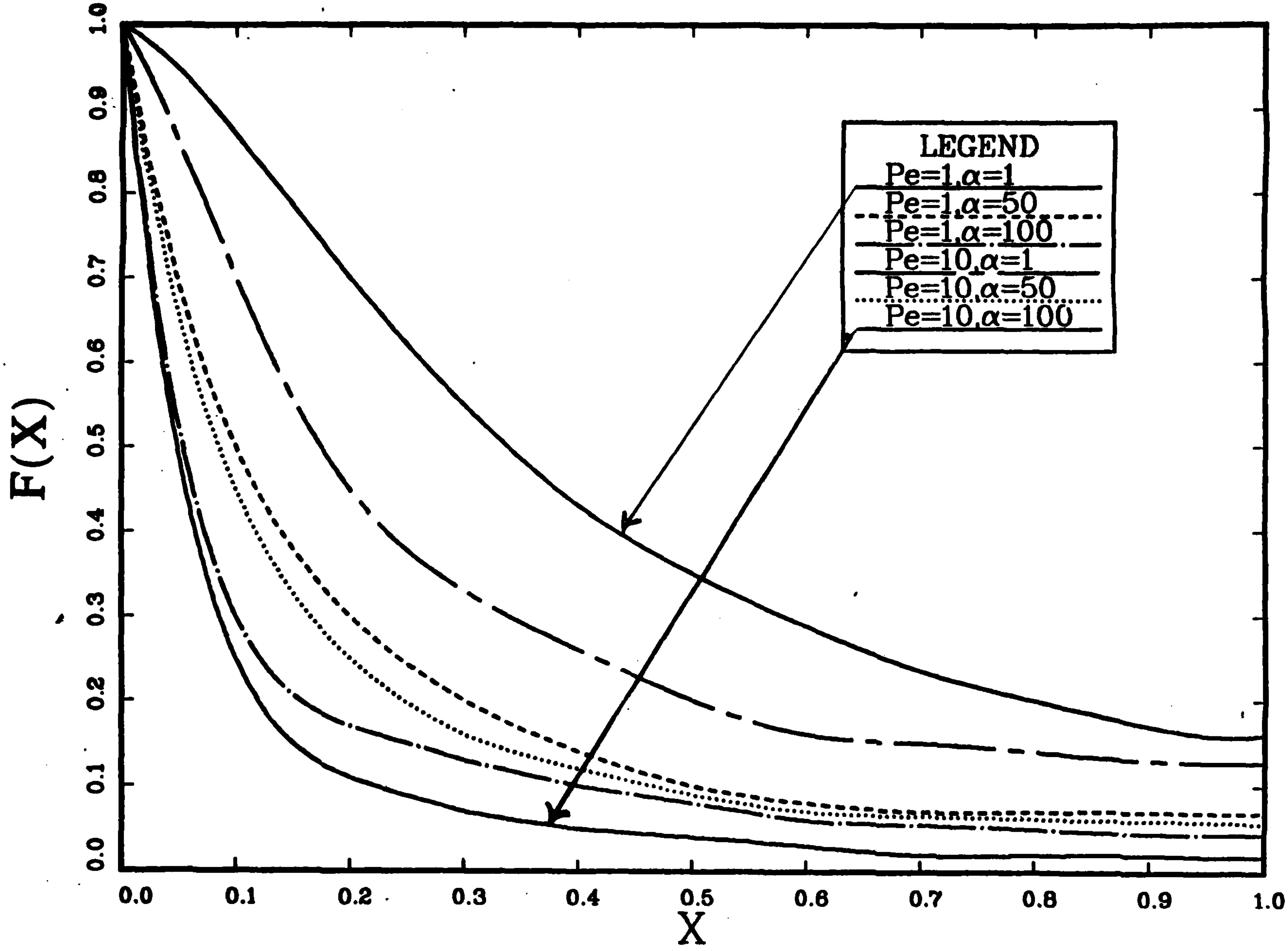


**Figure 2.** <u>Axial Distribution of Bulk Concentration for Variable Electrostatic Fields (Rev = 30 and Swirl = 8).</u>

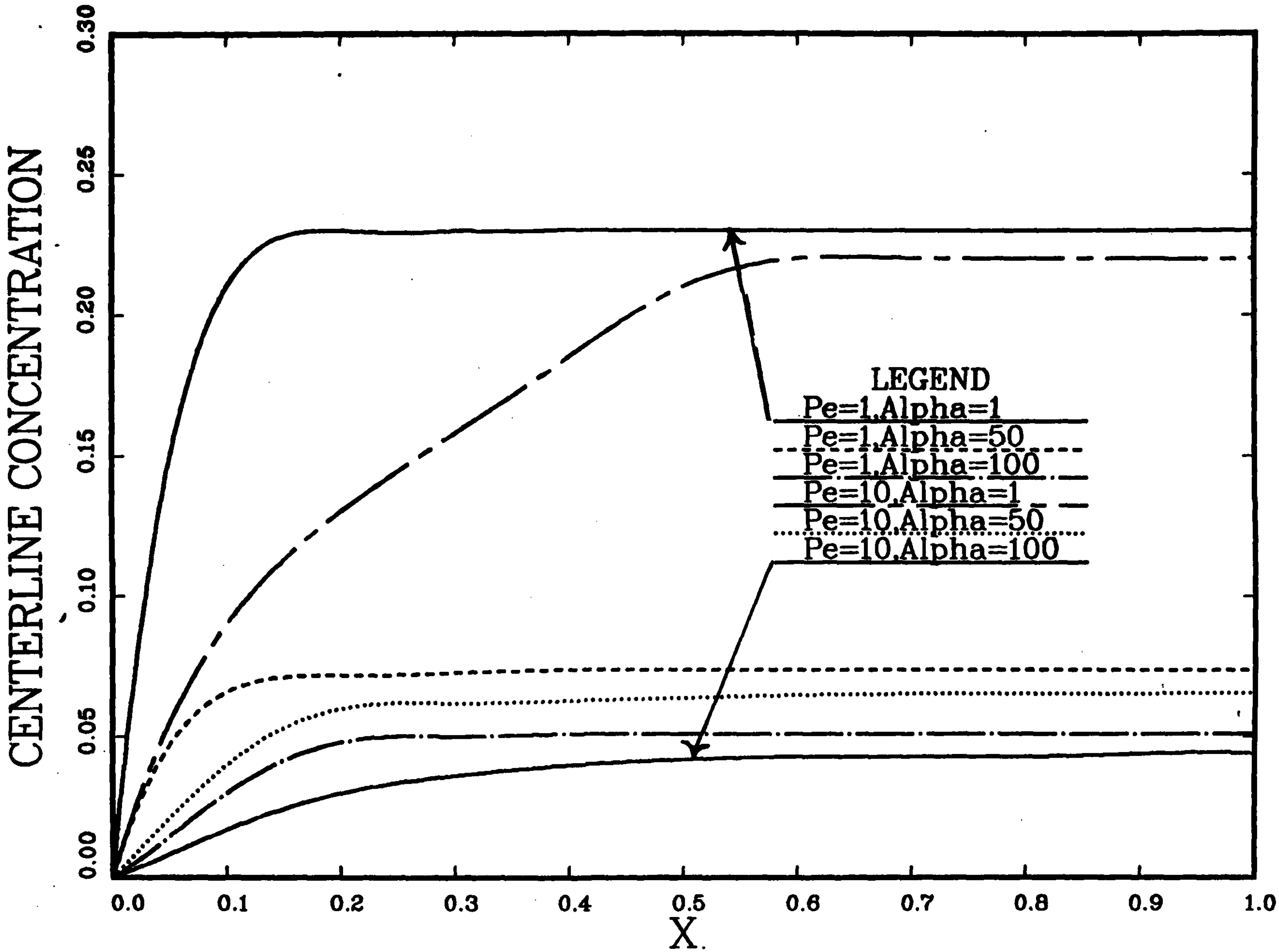


Figure 3. Axial Distribution of the Centerline Concentration at Different Electrostatic Fields.

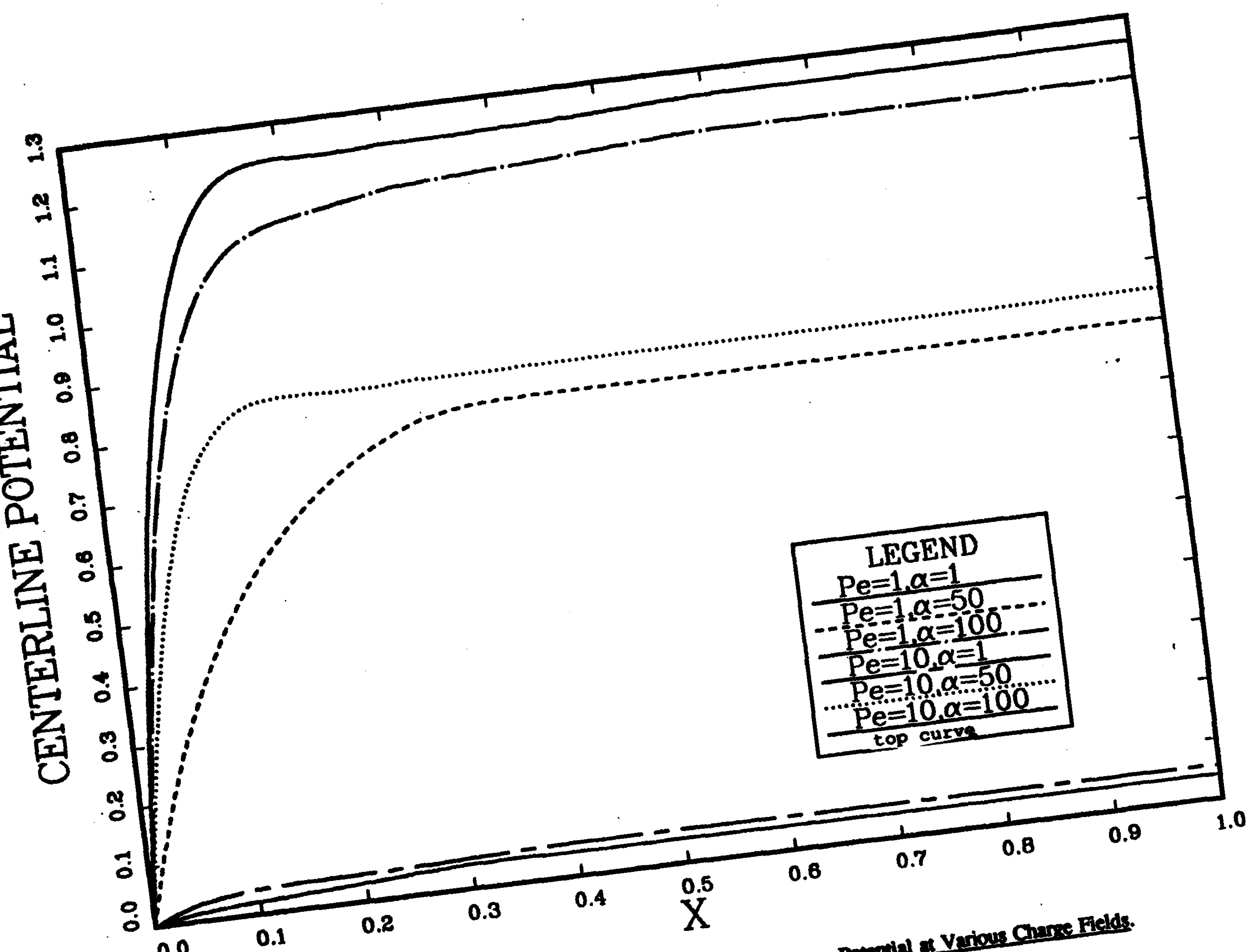


**Figure 4.** Axial Distribution of the Centerline Electrostatic Charge Potential at Various Charge Fields.

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## LIST OF SYMBOLS

| | | |
|---|---|---|
| $a$ | - | Radius of a particle |
| c | - | Particle concentration |
| $C^*$ | - | Dimensionless particle concentration |
| $D_p$ | - | Particle diffusivity |
| $F$ | - | Inverse of relaxation time |
| $m_p$ | - | Mass of a particle |
| $p$ | - | Fluid static pressure |
| $P$ | - | Dimensionless pressure |
| $P_e$ | - | Peclet number |
| $\dot{Q}$ | - | Rate of particle generation per unit of volume |
| $r$ | - | Radial coordinate |
| $R$ | - | Dimensionless radial coordinate, $r/R_o$ |
| $Rey$ | - | Reynolds number |
| $R_o$ | - | Pipe radius |
| $S$ | - | Swirl ratio |
| $u$ | - | Radial velocity |
| $U$ | - | Dimensionless radial velocity |
| v | - | Tangential velocity |
| V | - | Dimensionless tangential velocity |
| $w$ | - | Axial velocity |
| $\overline{w}$ | - | Mean axial velocity |
| $W$ | - | Dimensionless axial velocity |
| $X$ | - | Transformation variable |

| | | |
|---|---|---|
| $X'$ | - | First derivative of X with respect to Z |
| $z$ | - | Axial coordinate |
| $Z$ | - | Dimensionless axial coordinate |
| $\alpha$ | - | Electrostatic charge parameter |
| $\Gamma$ | - | Circulation |
| $\varepsilon_o$ | - | Permitivity of free space |
| $\Delta R$ | - | Radial change |
| $\Delta X$ | - | Axial change |
| $\overline{\mu}$ | - | Viscosity of material constituting fluid phase |
| $\nu$ | - | Kinematic viscosity of fluid |
| $\overline{\nu}$ | - | Kinematic viscosity of fluid phase material |
| $\rho$ | - | Fluid density |
| $\zeta$ | - | Vorticity |
| $\Psi$ | - | Stream function |
| $\Gamma^*, \zeta^*, \Psi^*$ | - | Dimensionless circulation, vorticity, and stream functions, respectively |
| $\phi$ | - | Electrostatic potential |
| $\phi^*$ | - | Dimensionless electrostatic potential |
| $\Omega$ | - | Constant angular velocity |

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